DELTA RISK MANAGEMENT STRATEGY

INITIAL TECHNICAL FRAMEWORK PAPER

PROBABILISTIC SEISMIC HAZARD ANALYSIS FOR GROUND SHAKING AND ESTIMATION OF EARTHQUAKE SCENARIO PROBABILITIES

Prepared by:
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Prepared for:
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Probabilistic Seismic Hazard Analysis for Ground Shaking and Estimation of Earthquake Scenario Probabilities

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Foreword

The purpose of the Delta Risk Management Strategy (DRMS) Initial Technical Framework (ITF) is to guide the analysis of specific technical topics as they relate to assessing potential risks to Delta levees and assets resulting from various potential impacts (e.g., floods, earthquakes, subsidence, and climate change). These ITFs are considered "starting points" for the work that is to proceed on each topic. As the work is developed, improvements or modifications to the methodology presented in this ITF may occur.

The effects of earthquakes may be the most significant natural hazard that can impact the Delta levees. In this ITF paper, we describe the approach, methodology, inputs, issues, and project tasks that will be performed to assess the probabilities of the levels and character of earthquake ground-shaking events that will contribute to the risk of levee failure in the Delta. The general approach of performing a probabilistic seismic hazard analysis (PSHA) is standard practice in the engineering seismology/earthquake engineering community (McGuire 2004) and the computations will be state-of-the-art.

The PSHA methodology to be used in this study allows for the explicit consideration of epistemic uncertainties and inclusion of the range of possible interpretations of components in the seismic hazard model, including seismic source characterization and ground motion estimation. Uncertainties in models and parameters are incorporated into the hazard analysis through the use of logic trees.

A product required of the seismic hazard analysis are the probabilities of occurrence of all plausible earthquake events (defined by their locations, magnitudes, and ground motions). These will be used to develop estimates of risk (defined as the annual probability of seismically induced levee failure) at selected times over the next 200 years (e.g., 2006, 2056, etc.). The products of the PSHA will include hazard-consistent site-specific acceleration response spectra and time histories at selected levee sites distributed throughout the Delta area and an algorithm that can serve as input to the risk quantification.

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1.0 INTRODUCTION

The effects of earthquakes may be the most significant natural hazard that can impact the Delta levees. This is one of several topical area methodology Initial Technical Framework (ITF) papers prepared for the Delta Risk Management Strategy (DRMS) Project that describes an approach to evaluate the risk of failure of the Delta levees under present as well as foreseeable future conditions and to develop a risk management strategy to reduce and manage the risk. In this ITF paper, we describe the approach, methodology, inputs, issues, and project tasks that will be performed to assess the probabilities of the levels and character of earthquake ground-shaking events that will contribute to the risk of levee failure in the Delta. The general approach of performing a probabilistic seismic hazard analysis (PSHA) is standard practice in the engineering seismology/earthquake engineering community (McGuire 2004) and the computations will be state-of-the-art.

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2.0 APPROACH

We propose that this study's approach be consistent with the guidelines for a Level 2 analysis as defined by the Senior Seismic Hazard Analysis Committee (SSHAC 1997). In SSHAC terminology, the TI or Technical Integrator is defined as: "a single entity (individual, team, company, etc.) who is responsible for ultimately developing the composite representation of the informed technical community (herein called the community distribution) for the issues using the TI approach. This could involve deriving information relevant to an issue from the open literature or through discussions with experts." In a Level 2 analysis, the TI interacts with proponents and resource experts to identify issues and interpretations and estimates the community distribution. This Level 2 study will be further enhanced by conducting a workshop with knowledgeable researchers from the USGS, CGS, and other organizations.

The TI in this study consists of the SHTAT: Ivan Wong, URS Task Leader; Kevin Coppersmith, Coppersmith Consulting; Kathryn Hanson, Geomatrix Consultants; Walter Silva, Pacific Engineering & Analysis; Jeff Unruh, Lettis & Associates; and Robert Youngs, Geomatrix Consultants. The PSHA calculations will be performed by URS. Kevin Coppersmith and Ivan Wong will serve as facilitators for developing the seismic source and ground motion inputs, respectively.

3.0 METHODOLOGY

A PSHA is an evaluation of the ground motion that will be exceeded at a specified annual frequency or probability. The inputs to a PSHA are the same as those used in a deterministic analysis of ground motion hazard plus the assessment of the frequency of occurrence of the earthquakes. The following steps are taken in a PSHA somewhat similar to a deterministic analysis:

- Identify all seismic sources that can generate strong ground shaking at the site.
- Characterize each seismic source in terms of location, geometry, sense of slip, maximum magnitude, and earthquake occurrence rates for all magnitudes of significance to the site hazard (typically moment magnitude [M] ≥ 5).
- Select ground motion attenuation relationships appropriate for the seismic sources, seismotectonic setting, and site conditions.
- Calculate the probabilistic hazard using a qualified computer program. The hazard can be expressed in terms of seismic hazard curves and a Uniform Hazard Spectrum (UHS).

The seismic hazard approach used in this study is based on the model developed principally by Cornell (1968). The occurrence of earthquakes on a fault is assumed to be a Poisson process. The Poisson model is widely used and is a reasonable assumption in regions where data are sufficient to provide only an estimate of average recurrence rate (Cornell 1968). When there are sufficient data to permit a time-dependent estimate of the occurrence of earthquakes, the probability of exceeding a given value can be modeled as an equivalent Poisson process in which a variable average recurrence rate is assumed.

The probability that a ground motion parameter "Z" exceeds a specified value "z" in a time period "t" is given by:

$$p(Z > z) = 1 - e^{-\nu(z)\bullet t} \tag{1}$$

where $\nu(z)$ is the annual mean number (or rate) of events in which Z exceeds z. It should be noted that the assumption of a Poisson process for the number of events is not critical. This is because the mean number of events in time t, $\nu(z)\bullet t$, can be shown to be a close upper bound on the probability $p(Z > z)$ for small probabilities (less than 0.10) that generally are of interest for engineering applications. The annual mean number of events is obtained by summing the contributions from all sources, that is:

$$\nu(z) = \sum_n \nu_n(z) \tag{2}$$

where $\nu_n(z)$ is the annual mean number (or rate) of events on source n for which Z exceeds z at the site. The parameter $\nu_n(z)$ is given by the expression:

$$\nu_n(z) = \sum_i \sum_j ß_n(m_i)\bullet p(R=r_j|m_i)\bullet p(Z>z|m_i,r_j) \tag{3}$$

where:

$ß_n(m_i)$ = annual mean rate of recurrence of earthquakes of magnitude increment m_i on source n;

$p(R=r_j|m_i)$ = probability that given the occurrence of an earthquake of magnitude m_i on source n, r_j is the closest distance increment from the rupture surface to the site;

$p(Z > z|m_i,r_j)$ = probability that given an earthquake of magnitude m_i at a distance of r_j, the ground motion exceeds the specified level z.

The calculations will be made using the computer program HAZ38 developed by Norm Abrahamson. An earlier version of this program has been validated as part of PG&E's submittal to the NRC and the new features in this version will also be validated as part of ongoing URS work for the U.S. Department of Energy.

4.0 UNCERTAINTIES

The most recent PSHA studies distinguish between two types of uncertainty, namely epistemic uncertainty and aleatory variability. Aleatory variability (sometimes called randomness) is probabilistic variability that results from natural physical processes. The size, location, and time of the next earthquake on a fault and the details of the ground motion are examples of quantities considered aleatory. In current practice, these quantities cannot be predicted, even with the collection of additional data. Thus, the aleatory component of uncertainty is irreducible. The second category of uncertainty is epistemic, which results from imperfect knowledge about the process of earthquake generation and the assessment of their effects. An example of epistemic uncertainty is the shape of the magnitude distribution for a given seismic source. In principle, this uncertainty can be reduced with advances in knowledge and the collection of additional data.

These two types of uncertainty are treated differently in advanced PSHA studies. Integration is carried out over aleatory variabilities to get a single hazard curve, whereas epistemic uncertainties are expressed by incorporating multiple hypotheses, models, or parameter values. These multiple interpretations are each assigned a weight and propagated through the analysis, resulting in a suite of hazard curves and their associated weights. Results are presented as curves showing statistical summaries (e.g., mean, median, fractiles) of the exceedance probability for each ground motion amplitude. The mean and median hazard curves convey the central tendency of the calculated exceedance probabilities. The separation among fractile curves conveys the net effect of epistemic uncertainty about the source characteristics and ground motion prediction on the calculated exceedance, and provide a measure of confidence in the mean hazard estimate.

5.0 ASSUMPTIONS, CONSTRAINTS, AND LIMITATIONS

As described in SSHAC (1997), the model of randomness (aleatory variability) of earthquake behavior underlies virtually all PSHAs. A model is a mathematical representation of a conceptual model that is based on established scientific and engineering principles and from which the approximate behavior of a system, process, or phenomenon can be calculated within determinable limits of uncertainty. A limitation of models is that they only approximate the behavior of a physical process and cannot capture its every detail. There are also uncertainties in the parameters that are required by the model, which are generally due to the availability and uncertainties of data. The components of the aleatory model are in simplistic terms those that (1) characterize the seismicity in the vicinity of a site and (2) represent the predicted ground motion effect at a site given an earthquake of specified magnitude occurring at a given distance. SSHAC (1997) endorses this model for all but "certain uncommon cases where the available information may permit or require specific deviations." As with any effective presentation of nature, the model represents a compromise between complexity, availability of information, and sensitivity of the results (SSHAC 1997).

A key assumption of the standard PSHA model described above is that earthquake occurrence can be modeled as a Poisson process. The occurrence of ground motions at the site in excess of a specified level is also a Poisson process, if (1) the occurrence of earthquakes is a Poisson process, and (2) the probability that any one event will result in ground motions at the site in excess of a specified level is independent of the occurrence of other events.

In a significant departure from standard PSHAs, which assume a Poissonian process, time-dependent hazard will be included in the analysis using one or more of several possible models that were considered by WGCEP (2003). The DRMS Project will need to evaluate the seismic hazard at selected times over the next 200 years. Based on the results of the WGCEP (2003), there is an increasing probability of a large ($\mathbf{M} \geq 6.7$) earthquake occurring in the San Francisco Bay region in the period 2002 to 2031. The probability in 2002 was 62% and this value will increase with time. Inclusion of time-dependent earthquake occurrence probabilities in PSHA has been done in the past (e.g., the PSHA recently completed for evaluation of the BART system seismic hazards) and can be readily incorporated into the PSHA to be performed for the DRMS Project.

6.0 INFORMATION REQUIREMENTS

The basic inputs required for the PSHA and the risk analysis are the seismic source model and the ground motion attenuation relations or more accurately ground motion predictive equations. We describe these inputs in the following.

6.1 Seismic Source Model

Seismic source characterization is concerned with three fundamental elements: (1) the identification location and geometry of significant sources of earthquakes; (2) the maximum size of the earthquakes associated with these sources; and (3) the rate at which they occur. In this study, the dates of past earthquakes on specific faults are also required in addition to the frequency of occurrence. The source parameters for the significant faults in the site region (generally within about 100 km) are characterized for input into the hazard analyses. Both areal source zones and Gaussian smoothing of the historical seismicity will be used in the PSHA to account for the hazard from background earthquakes.

The guiding philosophy for characterizing seismic sources in this study is the following. The fundamental seismic source characterization will come from the work done by the U.S. Geological Survey's (USGS) Working Group on Northern California Earthquake Potential (WGNCEP 1996) and the Working Group on California Earthquake Probabilities (WGCEP 2003) and on the California Geological Survey's (CGS) seismic source model used in the USGS National Hazard Maps (Cao et al. 2003). This characterization will be updated and revised locally based on new published information. Also, additional and more detailed characterization of potential seismic sources in the western margin of the Great Valley will be included (Figure 1), in order to fully capture the range of assessments that might affect the Delta region.

Faults

Based on reviews of published and unpublished data, a model of the active and potentially active seismogenic faults has been developed by URS for the greater San Francisco Bay region (Figure 1). Each seismic source has been characterized using the latest geologic, seismological, and paleoseismic data and the currently accepted models of fault behavior developed by the WGNCEP (1996), WGCEP (2003), and on the CGS seismic source model used in the USGS National Hazard Maps (Cao et al. 2003). The major study recently completed by the WGCEP (2003) entitled "Earthquake Probabilities in the San Francisco Bay Region: 2002-2031" describes and summarizes the current understanding of the major faults in the San Francisco Bay area. We have adopted their seismic source model for the San Andreas, Hayward/Rodgers Creek, Concord/Green Valley, San Gregorio, Greenville, and Mt. Diablo thrust faults in our analyses. The characterization of the Calaveras fault has been slightly modified by WLA and URS. The characterizations of other faults such as the Sargent and Foothill thrust belt are based to a large extent on the CGS model (Cao et al. 2003) and other available studies.

Of particular significance are the blind faults adjacent to the Delta including the Roe Island, Potrero Hills, and Los Medanos taken from Unruh (WLA, personal communication, 2003), the Gordon Valley and Trout Creek faults from O'Connell et al. (2001), and the Western Tracy and Vernalis segments of the Coast Ranges-Sierran Block boundary zone (CRSB) (Sowers and Ludwig 2000) (Figure 1). The seismogenic potential of the Midland fault, which transects beneath much of the Delta area is also being assessed (Figure 1) (J. Unruh, WLA, personal communication, 2006). The seismic source model including the source parameters of the blind faults will be reviewed and updated by the SHTAT.

Uncertainties in determining recurrence models can significantly impact the hazard analysis. We will consider the truncated exponential, maximum-magnitude, and characteristic recurrence models, with various weights depending on the source geometry and type of rupture model. The weighting of these recurrence models, recurrence intervals for the major faults from WGCEP (2003), and slip rates in the URS model will be critically reviewed prior to use in the PSHA.

<u>Fault Creep (Aseismic Slip) and the R Factor</u>

Some faults or sections of faults are thought to move in a continuous aseismic manner, i.e., they slip without generating large earthquakes. The San Juan Bautista segment of the San Andreas fault is the best example of a creeping fault segment. Fault creep has been documented along portions of the Hayward, Calaveras, San Andreas, and Concord faults in the San Francisco Bay region. However, fault creep is still poorly understood. The primary indicator of the presence of aseismic slip at depth is the observation of surficial fault creep (e.g., Galehouse 1995). If surficial fault creep is not observed, there is little reason to suspect that it is a significant fault attribute at seismogenic depths. If surficial fault creep is observed, aseismic slip may extend to seismogenic depths beneath that section of that fault and can account for a significant portion of the slip rate available for earthquake generation (WGCEP 2003).

WGCEP (2003) accounted for aseismic slip through a seismic slip factor R that varies from 0, where all slip rate is accounted for by aseismic slip, to 1.0, where all of the slip rate is accounted for by earthquakes. Regional tectonic models based on geodetic observations collected in the San Francisco Bay region in the last few decades are the primary basis for determining the *R* values. The R values affect the maximum magnitude of each fault by reducing the rupture area used to calculate magnitudes. The incorporation of the R values in the PSHA will need to be evaluated by the SHTAT. WGCEP (2003) did not specify the areas of aseismic slip on individual faults and thus where they are assumed may affect the rupture distance used in attenuation relationships.

Time-Dependent Hazard

In their analyses to estimate earthquake probabilities along the major faults in the San Francisco Bay Area, the WGCEP used several models including non-Poissonian models that are time dependent, i.e., they account for the size and time of the last earthquake. In this study, the probabilities of occurrence for all significant and plausible earthquake scenarios for each seismic source at specified times over the next 200 years are required for the risk analysis. This requirement mandates heavy reliance on the results of WGCEP (2003). For many seismic sources, insufficient information exists to estimate time-dependent probabilities of occurrence and they will have to be treated in a Poissonian manner. In the PSHA for the DRMS Project, we will also incorporate an element of time-dependent hazard using the WGCEP (2003) fault characterization. The degree to which time-dependent hazard is included will be decided by the SHTAT in consultation with DWR.

Background Seismicity

To account for the hazard from background (floating or random) earthquakes in the PSHA that are not associated with known or mapped faults, regional seismic source zones were used. In most of the western U.S., the maximum magnitude of earthquakes not associated with known faults usually ranges from **M** 6 to 6½. Repeated events larger than these magnitudes generally produce recognizable fault-or-fold related features at the earth's surface (e.g., dePolo 1994). An example of a background earthquake is the 1986 **M** 5.7 Mt. Lewis earthquake that occurred east of San Jose.

Earthquake recurrence estimates of the background seismicity in each seismic source zone are required. We proposed the site region be divided into two regional seismic source zones: the Coast Ranges and Central Valley. The recurrence parameters for the Coast Ranges source zone can be adopted from Youngs et al. (1992). They calculated values for background earthquakes based on the historical seismicity record after removing earthquakes within 10-km-wide corridors along each of the major faults. The recurrence values for the Central Valley zone have been estimated by URS. Another alternative background zonation will represent the blocks between the identified faults as individual source zones. The proposed maximum earthquake for source zones is **M** 6.5 ± 0.3. The treatment and characterization of background seismicity will be reviewed by the SHTAT.

6.2 Attenuation Relations

To characterize the attenuation of ground motions in the PSHA, we propose using empirical attenuation relationships appropriate for the western U.S., particularly coastal California. All relationships provide the attenuation of peak ground acceleration and response spectral acceleration (5% damping). Weighting of these attenuation relationships varies for the faults depending on their tectonic settings. In the past, crustal attenuation relationships for the western U.S. have been derived for the most part from California strong motion records.

New attenuation relations developed as part of the Next Generation of Attenuation (NGA) Project sponsored by the Pacific Earthquake Engineering Research (PEER) Center Lifelines Program have been released to the public. Two members of the SHTAT, Drs. Silva and Youngs are co-authors of two of the five relationships. These new attenuation relationships have a substantially better scientific basis than current relationships because they are developed through the efforts of five selected attenuation relationship developer teams working in a highly interactive process with other researchers who have: (a) developed an expanded and improved database of strong ground motion recordings and supporting information on the causative earthquakes, the source-to-site travel path characteristics, and the site and structure conditions at ground motion recording stations; (b) conducted research to provide improved understanding of the effects of various parameters and effects on ground motions that are used to constrain attenuation models; and (c) developed improved statistical methods used to develop attenuation relationships including uncertainty quantification. Review of the NGA relationships indicate that, in general, ground motions particularly at short-periods (e.g., peak acceleration) are significantly reduced particularly for very large magnitudes ($\mathbf{M} \geq 7.5$) compared to current relationships. These relations will be reviewed and weighted in the PSHA. Intra-event and inter-event aleatory uncertainties for each attenuation relationship will also be required for the risk analysis.

6.3 Site Conditions

A geologic site condition needs to be defined where the hazard will be calculated. Often this has been parameterized as a generic condition such as rock or soil or more recently the average shear-wave velocity (V_S) in the top 100 ft (V_S30) of a site. In this analysis, the hazard will be defined for a stiff soil site condition characterized by an average V_S30. The fragility estimates for the levees will be referenced to these ground motions. All of the NGA relationships use V_S30 as an input.

7.0 OUTPUTS/PRODUCTS

The products that will be generated in this analysis include:

1. The annual probabilities of occurrence at selected times over the next 200 years (e.g., 2006, 2056, etc.) of plausible earthquake events, defined by their location, magnitude, and ground motion amplitude, for all seismic sources that could impact the Delta.

2. The likelihood of multiple/simultaneous levee failures during individual scenario earthquakes will need to be estimated and thus the correlation in ground motions that occurs during an event will need to be accounted for in the risk analysis. A possible approach to track these correlations is to incorporate elements of PSHA code into the risk calculations code. Ground motions for each of the earthquake events (item 1) at each of the levee reach locations will be estimated and given these ground motions, the probability of levee failure will be computed.

3. ‘Standard’ PSHA results for six sites in the Delta area (Figure 2). The results will include: fractile hazard curves for all ground motion measures the 5th, 15th, 50th (median), 85th, and 95th percentiles, and the mean; M-D (magnitude-distance) deaggregated hazard results for all ground motion measures for 0.01, 0.001, 0.002 and 0.0004 annual probabilities of

exceedance; mean hazard curves for each seismic source for each ground motion measure. The seismic hazard results will be defined for a stiff soil condition.

4. Time-dependent seismic hazard results at individual sites (same as above) at selected times. These times have yet to be selected.

5. Earthquake time histories for the six sites in the Delta which will be used as input to levee performance evaluations. The earthquake time histories should be defined for a stiff soil site condition and for earthquakes that span the range of events (magnitude and distance) that contribute to the likelihood of levee failure. The specification of earthquake time histories will be coordinated with the levee vulnerability team.

6. Probabilistic ground shaking hazard maps for 2% and 10% probabilities of exceedance in 50 years (2475 and 475 year return periods, respectively) will be developed for the Delta area as defined in Figure 2. The maps will be for peak horizontal acceleration and 0.2 and 1.0 sec spectral accelerations, and a stiff soil site condition.

8.0 SPECIAL RESOURCE REQUIREMENTS

None anticipated.

9.0 PROJECT TASKS

- **Task 1: Review and Revision of the Seismic Source Model**

The URS seismic source model for the greater San Francisco region will be used as a "strawman" to review and revise to produce the final model for the PSHA calculations. The model will be transmitted to the SHTAT for their review prior to a team meeting in mid-May. Review comments will be discussed and they and any new issues raised will be resolved if possible. If future analyses are deemed necessary that can be performed within the current schedule, these will be recommended to the project management. A second team meeting to resolve remaining issues will be scheduled based on the outcome of meeting #1. It is important to note that some members of the SHTAT may be proponents of seismic source models that will need to be considered in the development of the seismic source model. However, in the process of seismic source model development, all SHTAT members will perform as objective experts and will consider the full range of all possible viable models and associated uncertainties. A meeting with the USGS, CGS, and other interested organizations and individual experts will be convened to present the seismic source model and discuss alternative models and potential issues. Based on this meeting, the model will be finalized.

- **Task 2: Selection of Attenuation Relationships**

The NGA ground motion attenuation relationships will be evaluated, selected, and weighted by a subgroup of the SHTAT.

- **Task 3: PSHA Calculations for Defining Earthquake Events and for Hazard at Specific Sites**

Based on Tasks 1 and 2, PSHA calculations will be performed for multiple sites throughout the study region. The results will define plausible earthquake events, defined by their location, magnitude, and ground motion. These results will be passed along to the fragility group for evaluation of the probability of failure, given these earthquake events. In addition, PSHA will be calculated for six selected sites. The results will be reviewed by the SHTAT and if deemed necessary recalculations will be performed and finalized. Final hazard results will consist of those products previously described.

- **Task 4: Development of Time Histories**

Earthquake time histories for selected sites will be developed based on spectral matching. The time histories will be representative of the range of earthquake scenarios that contribute to the likelihood of levee failure. One set of three-component time histories will be computed for each annual exceedance probability.

- **Task 5: Ground Shaking Hazard Maps**

Based on the PSHA, ground shaking maps for the Delta area will be developed for 2% and 10% exceedance probabilities in 50 years. The GIS maps will display peak horizontal acceleration and 0.2 and 1.0 sec spectral accelerations for a stiff soil site condition.

- **Task 6: Final Report and Review**

A final report that describes and summarizes the methodology and results of this study will be produced. A draft report will be reviewed by the SHTAT and revised. A subsequent draft will be submitted to DWR for their review and comment. DWR's comments will be addressed and incorporated into the final report. The final report will be transmitted to DWR for final approval and acceptance. The report and products will be provided to other members of the Project Team requiring ground motion inputs.

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Figures

Legal Delta Boundary V. 2002-4

Faults used in the hazard analysis

Bounds of delta islands

CRSB - Coast Range Sierran Block
SAF - San Andreas Fault

0 30 60 90 Kilometers

0 20 40 60 Miles

URS

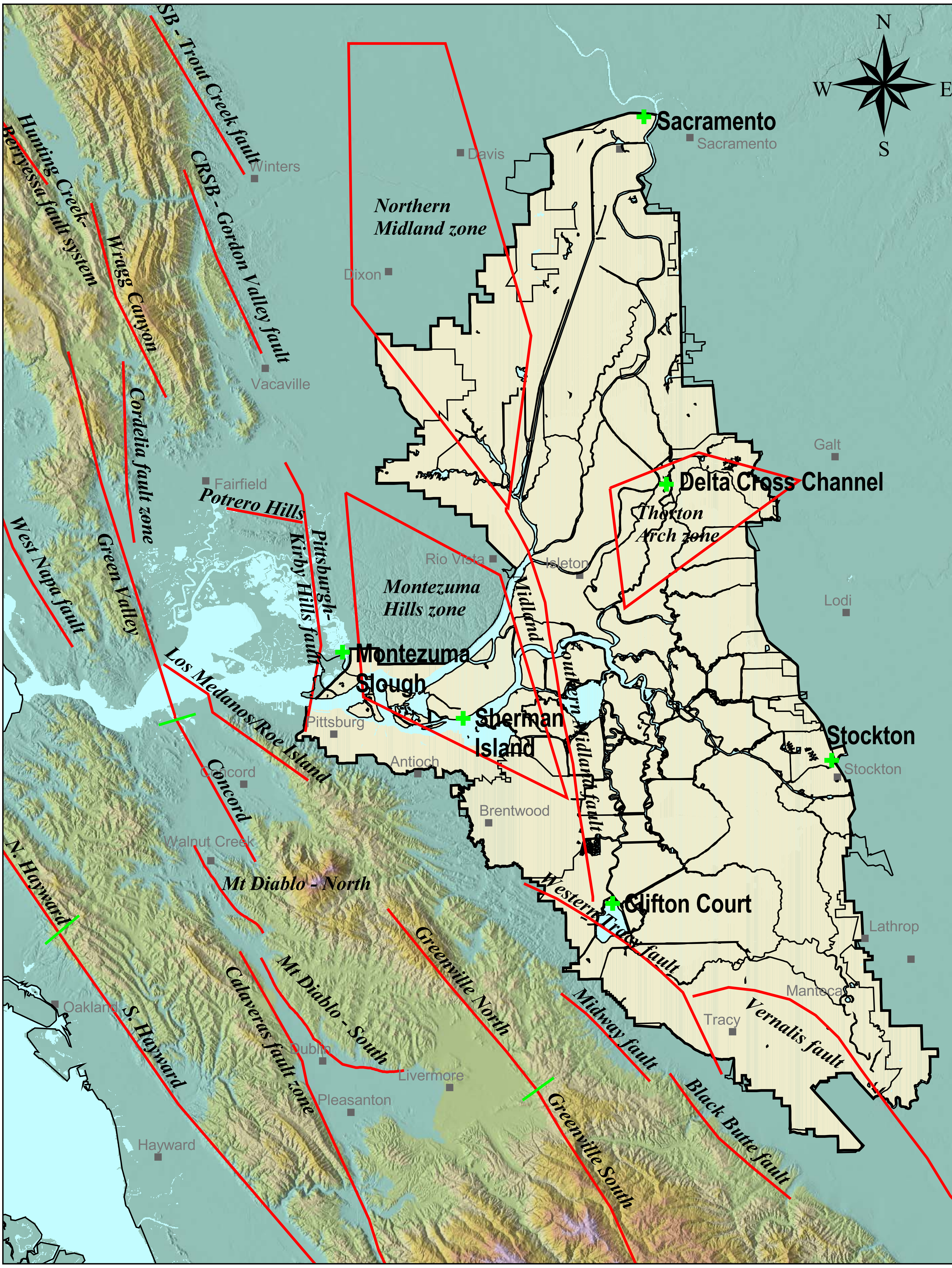
Delta Risk Analysis
California

Project No. 26815431

FAULTS IN THE
SAN FRANCISCO BAY REGION

Figure
1

Apr Path Name XXXXXXXXXXXX



0 10 20 30 Miles

0 10 20 30 40 50 Kilometers

Legal Delta Boundary V. 2002-4

Faults used in the hazard analysis

Bounds of delta islands

CRSB - Coast Range Sierran Block

URS	Delta Risk Analysis California Project No. 26815431	ACTIVE FAULTS IN THE SITE REGION	Figure 2

Apr Path Name XXXXXXXXXXXX